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Phenomenology of a String-Inspired Supersymmetric Model with Inverted Scalar Mass Hierarchy

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Abstract

Supersymmetric (SUSY) models with heavy sfermions ($m_{\tilde{f}} \sim 10$ TeV) in the first two generations and the third generation sfermion masses below 1 TeV can solve the SUSY flavor and the CP problems as well as satisfy naturalness constraints. We study the phenomenology of a string-inspired scenario and compare it with the minimal supergravity unified model (mSUGRA). The SUSY trilepton signature at the upgraded Tevatron, the $b \to s\gamma$ branching fraction and the neutralino dark matter relic density in this model can differ significantly from the mSUGRA model.

I. INTRODUCTION

Generic supersymmetric (SUSY) extensions of the standard model (SM) may generate large flavor-changing neutral current (FCNC) and CP violation effects. Many entries in the sfermion mass matrices and some CP-violating phases must be sufficiently suppressed to satisfy stringent experimental bounds, e.g. from the $K-\bar{K}$ mass difference, CP asymmetries in the kaon system, and the electric dipole moments of the electron and the neutron [1]. These quantities have been assumed to be small in the minimal supergravity unified model (mSUGRA) without much justification. Providing a satisfactory solution to the problem is one of the major motivations in SUSY model building [2–6].

Several models have been proposed to realize a scenario with heavy sparticles in the first two generations [3]. In these models the heavy soft masses are of order 10 TeV to solve the SUSY flavor and CP problems, while the third generation sfermions and the Higgs bosons still have soft masses of weak scale order, thus satisfying the naturalness condition constraints. This inverted scalar mass hierarchy is well motivated because the most stringent constraints from FCNC and CP violation processes only apply to the first two generations. (The first two generations can also be subject to naturalness constraints through a one-loop D-term which however is zero in unification models.) In Ref. [4], the D-term of an anomalous U(1) symmetry (which is common to many 4-D string models) has been used to generate an inverted mass hierarchy–the D-term dominates over the gravity-mediated F-term contribution to the sfermion soft masses if U(1) charges are appropriately assigned. In Ref. [5,6], the hierarchy is generated from grand-unified scale soft masses of order a few TeV through renormalization group (RG) evolution; the third generation sfermion and Higgs boson masses are highly suppressed at the weak scale because of the associated large third generation Yukawa couplings and the infrared fixed points of the RG equations. In the latter models, the gravitino mass is also of order of several TeV, solving the problem of late gravitino decay after the period of big bang nucleosynthesis [7].

In this Letter we first consider a string-inspired model that generates an inverted scalar mass hierarchy. This model consists of the minimal supersymmetric standard model superfields and two singlet chiral superfields S and T with nonzero F-component vacuum expectation values (VEVs). We assume $F_S \simeq 10^{-2} F_T \simeq M_W M_{pl}$, where M_W is the weak scale. Similar relations $F_S \ll F_T$ appear naturally in many models with gaugino condensation [8]. The gaugino mass is determined from the gauge kinetic term, which is of the form

$$\int d^2\theta \; \frac{S}{M_{pl}} W^a W_a \; . \tag{1}$$

This gives $m_{1/2} \simeq F_S/M_{pl} \simeq M_W$. The sfermion masses are determined from the Kähler potential, for which we take the following form

$$K(S,T,Q_i) \;=\; -\log(S+\bar{S}) - 3\log(T+\bar{T}) + (T+\bar{T})^{n_i} Q_i^\dagger Q_i, \tag{2}$$

where n_i is the overall modular weight for the matter field Q_i, and i the family index. Choosing $n_3 = -1$ and $n_{1,2} > -1$, we find

$$\tilde{m}_{1,2}, A_{1,2} \simeq \frac{F_T}{M_{pl}} \simeq 100 \; M_W, \qquad \tilde{m}_3, A_3 \simeq \frac{F_S}{M_{pl}} \simeq M_W, \tag{3}$$

where $\tilde{m}_i$ is the i-th generation sfermion mass. Therefore this choice of modular weights generates an inverted mass hierarchy at the string scale. The gravitino mass in this model, $m_{3/2} \simeq F_T/M_{pl} \simeq 100\ M_W$, is of order of 10 TeV. The form of the Kähler potential in Eq. (2) can be obtained in 4-D heterotic string models; indeed, fields from the untwisted sector have the modular weight -1, and our model corresponds to the moduli-dominated SUSY breaking scenario of Ref. [9].

In the following, we study the phenomenology of this model with an inverted scalar mass hierarchy (the ISM model). We set the first-two-generation sfermion masses and trilinear couplings at 5 TeV, and assume a common scalar mass (m_0) and a common trilinear coupling (A_0) for the third generation sfermions, along with a universal gaugino mass ($m_{1/2}$) at the grand unified scale ($M_{\rm GUT}$):

$$\begin{aligned} & m_{1/2}, \;\; \tilde{m}_1 = \tilde{m}_2 = 5 \;\; \text{TeV}, \;\; \tilde{m}_3 = m_0, \\ & A_1 = A_2 = 5 \;\; \text{TeV}, \;\; A_3 = A_0, \end{aligned} \tag{4}$$

where $m_0 \lesssim 1$ TeV. We take $A_0 = 0$ in our calculations since the value of A_0 does not significantly affect the results. Most of our conclusions depend only on the existence of a soft mass hierarchy and so should be generic, for example, they should apply to the models in Refs. [4,5].

At the weak scale, we choose $\tan\beta$ and sign of the μ parameter as free parameters. The value of $|\mu|$ and the Higgs-sector soft breaking bilinear parameter (B) are obtained by imposing the electroweak symmetry breaking conditions. In Table I, we present masses in both the ISM and the mSUGRA models with $\mu > 0$, $m_0 = 150$ GeV, $m_{1/2} = 200$ GeV, $\tan\beta = 3$ and 35, for the charged Higgs boson ($H^\pm$), the lighter chargino ($\chi^\pm_1$) and neutralinos ($\chi^0_{1,2}$), the lighter top and bottom squark ($\tilde{t}_1$,$\tilde{b}_1$), the lighter tau slepton ($\tilde{\tau}_1$), and the first generation squarks and sleptons.

We have employed one-loop renormalization group equations (RGEs) to evaluate the weak-scale SUSY particle masses and couplings with the boundary conditions in Eq. (4) at the unification scale. If two-loop RGEs are used, the third-generation sfermion masses at the weak scale might become unphysical for $\tilde{m}_{1,2} \gtrsim 22$ TeV and $m_0 \lesssim 4$ TeV [10], that corresponds to approximately $\tilde{m}_{1,2} \gtrsim 6$ TeV and $m_0 \lesssim 1$ TeV.

In this letter we present interesting phenomena in the ISM and the mSUGRA models: the trilepton signature at the upgraded Tevatron, the branching fraction of $b \to s\gamma$, and the relic density of the neutralino dark matter. These three processes can be complementary in distinguishing the inverted-scalar-mass hierarchy model and the minimal supergravity model.

II. TRILEPTON SIGNATURE AT THE UPGRADED TEVATRON

Trileptons from the associated production and decays of the lighter chargino ($\chi^\pm_1$) and the second lightest neutralino (χ^0_2) is probably the most promising channel to search for supersymmetric particles at the Tevatron Run II ($\sqrt{s} = 2$ TeV) [11–14]. The $\chi^\pm_1\chi^0_2$ associated production has a reasonably large cross section and the trilepton background from SM processes can be greatly reduced with suitable cuts.

The associated production of $\chi^\pm_1\chi^0_2$ occurs via quark-antiquark annihilation in the s-channel through a W boson and in the t and u-channels through squarks ($\tilde{q}$). In both the ISM

TABLE I. Masses (GeV) of relevant SUSY particles for $\mu > 0$.

Parameters	mSUGRA	mSUGRA	ISM	ISM
m_0	150	150	150	150
$m_{1/2}$	200	200	200	200
A_0	0	0	0	0
$\tan\beta$	3	35	3	35
$m_{H^\pm}$	405	252	398	248
$m_{\chi_1^\pm}$	142	148	143	150
$m_{\chi_2^0}$	144	149	146	150
$m_{\chi_1^0}$	76	80	78	81
$m_{\tilde{t}_1}$	312	333	307	327
$m_{\tilde{b}_1}$	427	373	420	368
$m_{\tilde{\tau}_1}$	172	116	172	117
$m_{\tilde{u}_L}$	469	468	5015	5015
$m_{\tilde{u}_R}$	455	455	5013	5013
$m_{\tilde{d}_L}$	474	475	5015	5015
$m_{\tilde{d}_R}$	455	455	5013	5013
$m_{\tilde{e}_L}$	212	212	5002	5002
$m_{\tilde{e}_R}$	173	164	5001	5001
$m_{\tilde{\nu}_L}$	199	197	5002	5001

and mSUGRA models with $m_0 \gtrsim 200$ GeV, the up and down squarks are much heavier than the gauge bosons and the s-channel W-resonance amplitude dominates. In mSUGRA with $m_0 \lesssim 150$ GeV, the up and down squarks are relatively light and a destructive interference between the W boson and the squark exchange amplitudes can suppress the cross section by as much as 40%, compared to the s-channel contribution alone. For $m_0 \lesssim 150$ and $\tan\beta \gtrsim 20$, production of $\tilde{\ell}\tilde{\nu}$ and $\tilde{\ell}\tilde{\ell}$ can enhance the mSUGRA trilepton signal [12].

The Yukawa couplings of the bottom quark (b) and the tau lepton (τ) are proportional to $\tan\beta$ and are greatly enhanced when $\tan\beta$ is large. In SUSY grand unified theories, the lighter tau slepton ($\tilde{\tau}_1$) and the lighter bottom squark ($\tilde{b}_1$) can become lighter than other SUSY particles for large $\tan\beta$.

In the ISM model, $\chi_1^\pm$ and χ_2^0 decay dominantly into final states with (i) τ leptons for $\tan\beta \sim 3$, and (ii) b quarks and τ leptons for $\tan\beta \sim 35$. The contributions from $\tau-$leptonic decays enhance the trilepton signal substantially when soft cuts on lepton transverse momenta are used [12]. In mSUGRA, the leptonic branching fractions of $\chi_1^\pm$ and χ_2^0 depend on the values of $\tan\beta$, $m_{1/2}$ and m_0: (i) for $\tan\beta \sim 3$, $m_{1/2} \sim 200$ GeV and $m_0 \sim 100$ GeV, the dominant decays for $\chi_1^\pm$ and χ_2^0 are $\chi_1^\pm \to \tilde{\tau}_1\nu$, $\chi_2^0 \to \tilde{\ell}_R\ell$ and $\tilde{\tau}_1\tau$; (ii) for $\tan\beta \sim 35$ and $m_0 \lesssim 150$ GeV the $\chi_1^\pm$ and χ_2^0 decay dominantly into final states with τ leptons and b squarks; (iii) for $3 \lesssim \tan\beta \lesssim 40$ and 180 GeV $\lesssim m_0 \lesssim 400$ GeV, $\chi_1^\pm$ and χ_2^0 dominantly decay into final states with $q\bar{q}'\chi_1^0$.

Figure 1 shows the branching fractions of $\chi_2^0 \to \tau\bar{\tau}\chi_1^0, \ell = e, \mu$, and $\chi_2^0 \to \ell\bar{\ell}\chi_1^0, \ell = e, \mu$,

via virtual and real $\tilde{\tau}$ or $\tilde{\ell}$ in the ISM and mSUGRA models for $\tan\beta = 3$ and $\tan\beta = 35$. The branching fractions of $\chi_1^\pm \chi_2^0 \to 3\tau + X$ in the ISM model resemble those of large $\tan\beta$ in mSUGRA.

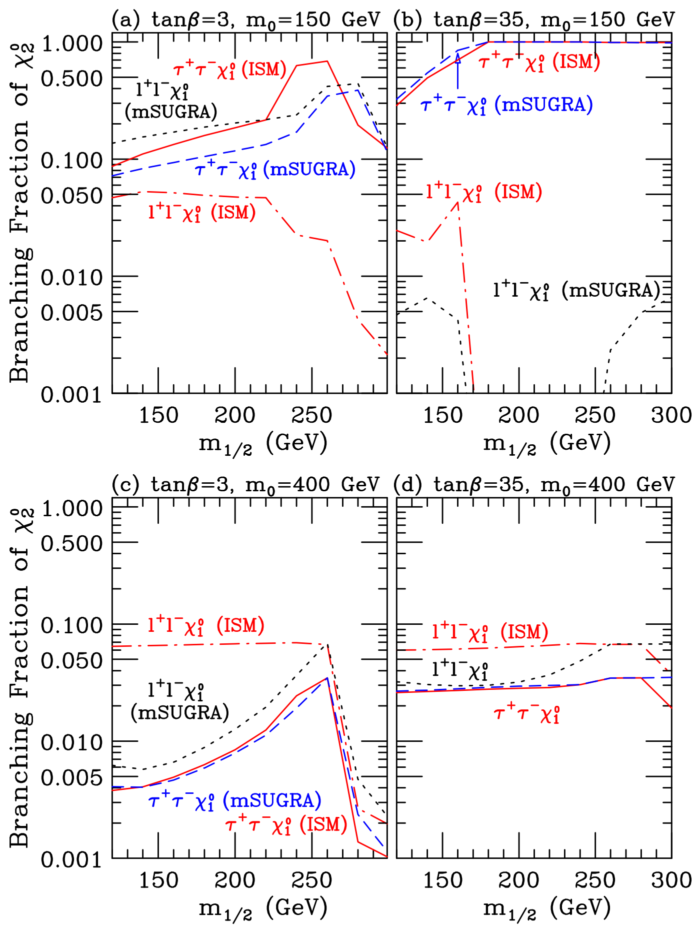

FIG. 1. Branching fractions of $\chi_2^0 \to \tau\bar{\tau}\chi_1^0$ in the ISM (solid) and the mSUGRA (dash) models as well as $\chi_2^0 \to \ell\bar{\ell}\chi_1^0$ in the ISM (dot-dash) and the mSUGRA (dot) models, for $\mu > 0$, $\tan\beta = 3$ and 35, and $m_0 = 150$ GeV and 400 GeV.

To assess the discovery potential of the upgraded Tevatron in searching for SUSY particles, we present results from simulations for the trilepton signal with an event generator and a simple calorimeter including our acceptance cuts. The ISAJET 7.44 event generator program [15] with the parton distribution functions of CTEQ3L [16] is employed to calculate the trilepton signal ($3\ell + \not{E}_T$) from all possible sources of SUSY particles. The background from $t\bar{t}$ is calculated with ISAJET as well.

Requiring three isolated leptons in each event with $p_T(\ell_{1,2,3}) > 11, 7, 5$ GeV, $|\eta(\ell_{1,2,3})| < 1, 2, 2$, along with missing transverse energy $\not{E} > 25$ GeV, and applying other acceptance cuts [12], we find that the major SM backgrounds are (i) $q\bar{q}' \to WZ + W\gamma \to \ell\nu\ell\bar{\ell}$ or $\ell'\nu'\ell\bar{\ell}$ ($\ell = e$ or μ) (ii) $q\bar{q}' \to WZ + W\gamma \to \ell\nu\tau\bar{\tau}$ or $\tau\nu\ell\bar{\ell}$ and subsequent τ leptonic decays, with one or both gauge bosons being virtual. We employed the programs MADGRAPH [17] and HELAS [18] to evaluate the background cross section of $p\bar{p} \to 3\ell + \not{E}_T + X$ from all these subprocesses. Additional backgrounds come from production of $t\bar{t}$ and $ZZ \to \ell\bar{\ell}\tau\bar{\tau}$ [12,13].

At the upgraded Tevatron with 30 fb^{-1} integrated luminosity (Run III), we expect about 59 SM background events and 38 signal events for a 5σ signal [12].

In Fig. 2, we present the cross section of $p\bar{p} \to$ SUSY particles $\to 3\ell + \not{E}_T + X$, versus $m_{1/2}$ for $\mu > 0$, $\tan\beta = 3$ and $\tan\beta = 35$. The dotted horizontal line denotes the 5σ signal cross sections for $\mathcal{L} = 30$ fb^{-1}. At large $\tan\beta$, the trilepton cross section in the ISM model is slightly larger than that of mSUGRA because the first two generation squarks are heavy in the ISM and the decays of $\chi_1^\pm \chi_2^0 \to 3\ell + X$ are enhanced. When $\tan\beta \sim 3$ the trilepton cross section is very sensitive to the value of m_0: (i) for $m_0 \sim 100$ GeV, the mSUGRA model yields a larger trilepton cross section from real decays of $\chi_2^0 \to \tilde{\ell}_R \bar{\ell} \to e\bar{e}$; (ii) for $m_0 \sim 400$ GeV, the mSUGRA trilepton cross section can be smaller by an order of magnitude because $\chi_1^\pm$ and χ_2^0 dominantly decay into final states with $q\bar{q}'\chi_1^0$.

We conclude that there are major differences in the mSUGRA and the ISM predictions for trileptons, particularly at low $\tan\beta$, that can differentiate these models. The mSUGRA predictions show a strong dependence on m_0, whereas the ISM predictions do not.

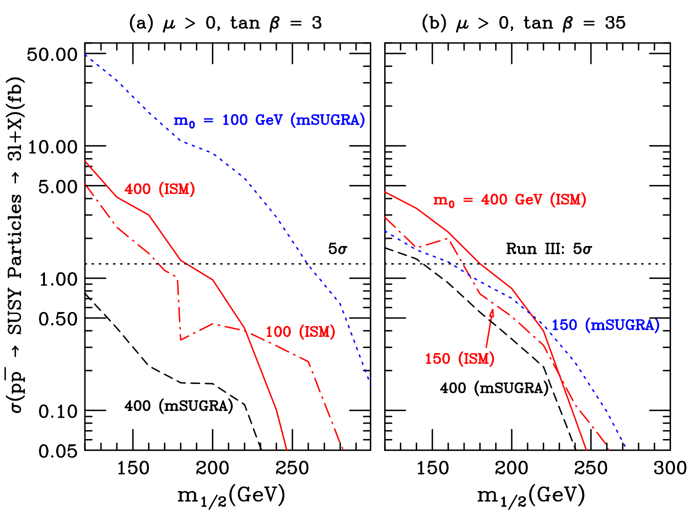

FIG. 2. Cross section of $p\bar{p} \to$ SUSY particles $\to 3\ell + X$ versus $m_{1/2}$, at $\sqrt{s} = 2$ TeV, with soft acceptance cuts, for $\mu > 0$, (a) $\tan\beta = 3$ and (b) $\tan\beta = 35$ with $m_0 = 100$ GeV or 150 GeV in the ISM (dot-dash) and the mSUGRA (dot) models as well as $m_0 = 400$ GeV in the ISM (solid) and the mSUGRA (dash) models. The horizontal dotted line denotes the cross section of a 5 σ signal for $\mathcal{L} = 30$ fb^{-1}.

In both the mSUGRA and the ISM scenarios the trilepton channel could provide valuable information about the value of $m_{1/2}$, because the weak-scale gaugino masses are related to the universal gaugino mass parameter $m_{1/2}$ by

$$m_{\chi_1^\pm} \sim m_{\chi_2^0} \sim 0.8 m_{1/2}. \tag{5}$$

For $m_{1/2} = 120$ GeV and $m_0 = 400$ GeV, the chargino mass is 90 GeV for $\tan\beta = 3$ and 92 GeV for $\tan\beta = 35$. The chargino search at LEP 2 [19] has excluded charginos with $m_{\chi_1^+} < 95$ GeV at the 95% confidence level. The experiments at the Tevatron may probe a substantial region not accessible at LEP 2 [12,13].

III. CONSTRAINTS FROM $b \to s\gamma$

The experimental measurements of the branching fraction $B(b \to s\gamma)$ by the CLEO [20] and LEP collaborations [21] place tight constraints on the parameter space of various models and offer guidance for model building. In the minimal supersymmetric model (MSSM), there are dominant contributions from loop diagrams involving (i) the W boson and the quarks, (ii) the charged-Higgs boson ($H^\pm$) and the quarks, and (iii) the charginos ($\chi_i^\pm$) and the squarks. The loop diagrams involving neutralinos and gluinos are known to be negligible in the MSSM and the mSUGRA model [22–24] and we neglect these contributions here in both models. As the value of $\tan\beta$ becomes large, the form factors from the charged-Higgs-boson diagrams slightly increase, while the form factors of the chargino loops are greatly enhanced and have opposite sign to the $W-$loop. The charged-Higgs-boson loop interferes constructively with the W-loop; the contributions from chargino loop have constructive interference with the W-loop when $\mu < 0$, but destructive interference with the W-loop when $\mu > 0$. As a result, the predicted value of $B(b \to s\gamma)$ in the MSSM is larger than the SM when $\mu < 0$ and can be smaller than the SM when $\mu > 0$. It has been found that the experimental limits of $b \to s\gamma$ disfavor most of mSUGRA parameter space when $\tan\beta \gtrsim 10$ and $\mu < 0$ [23,25].

Figure 2 shows the branching fraction of $b \to s\gamma$ versus $m_{1/2}$ in the ISM and mSUGRA models with $\mu > 0$, for (a) $\tan\beta = 3$ and (b) $\tan\beta = 35$. Also shown are experimental limits at 95% confidence level (C.L.) ($2.0 \times 10^{-4} < B(b \to s\gamma) < 4.5 \times 10^{-4}$) from the CLEO collaboration [20].

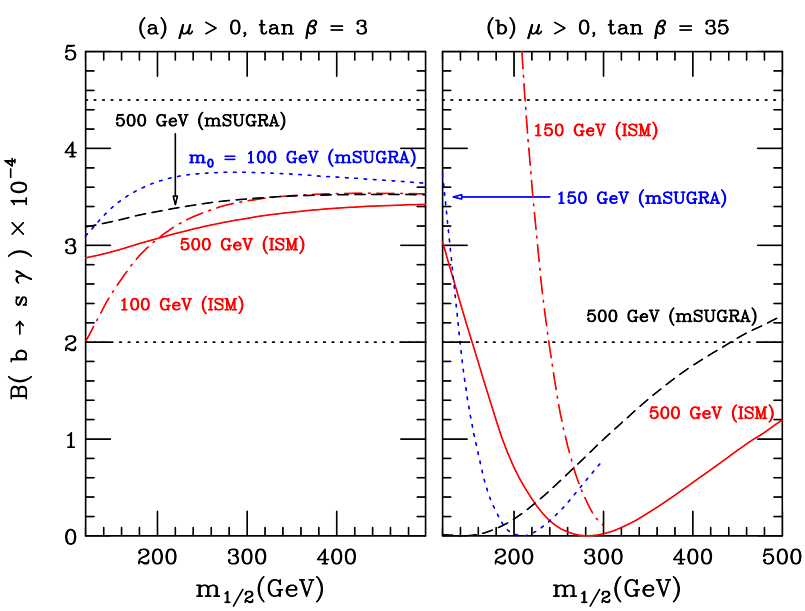

FIG. 3. Branching fraction of $b \to s\gamma$ versus $m_{1/2}$ for $\mu > 0$, (a) $\tan\beta = 3$ and (b) $\tan\beta = 35$ with $m_0 = 100$ GeV or 150 GeV in the ISM (dot-dash) and the mSUGRA (dot) models as well as $m_0 = 500$ GeV in the ISM (solid) and the mSUGRA (dash) models. The horizontal dotted lines are the 95% C.L. limits for the CLEO measurements.

When $\tan\beta \sim 3$, the predicted branching fractions in both the ISM and the mSUGRA models are within the range favored by experimental measurements. The branching fraction

in the ISM model is smaller than that in mSUGRA.

For $\tan\beta \sim 35$ and $m_0 \lesssim 500$ GeV, a destructive interference occurs in both the ISM and mSUGRA models between loops involving the first two generation squarks and loops involving the third generation squarks. This destructive interference severely reduces the mSUGRA chargino contribution, and makes $B(b \to s\gamma)$ in mSUGRA much smaller than the experimental lower limit. In contrast, the value of $B(b \to s\gamma)$ in the ISM model can be within the allowed experimental limits in a sizable region of the $(m_{1/2}, m_0)$ plane.

IV. THE NEUTRALINO RELIC DENSITY

In SUSY theories with conservation of R-parity the lightest SUSY particle (LSP) is an attractive candidate for cosmological dark matter because it is stable [30]. In most of the mSUGRA parameter space, the lightest neutralino (χ_1^0) is the LSP. For models with gauge mediated SUSY breaking or R-parity violation, the χ_1^0 decays and cannot be a dark matter candidate.

The matter density of the Universe (ρ) is commonly described in terms of a relative mass density $\Omega = \rho/\rho_c$ with $\rho_c = 3H_0^2/8\pi G_N \simeq 1.88 \times 10^{-29} h^2$ g/cm^3 the critical density to close the Universe. Here, H_0 is the Hubble constant, $h = H_0/(100$ km sec^{-1} Mpc$^{-1})$, and G_N is Newton's gravitational constant. Based on the matter density $\Omega_m \simeq 0.3 \pm 0.05$ inferred from cluster X-ray [26] and supernova [27] observations, the baryon density $\Omega_b \simeq 0.019 \pm 0.0024$ [29] from nucleosynthesis, and the Hubble constant $h \simeq 0.65 \pm 0.08$ [28] the cosmologically interesting region for the neutralino dark matter relic density ($\Omega_{\chi_1^0} = \Omega_m - \Omega_b$) is

$$0.05 \lesssim \Omega_{\chi_1^0} h^2 \lesssim 0.3. \tag{6}$$

The neutralino dark matter relic density has been studied extensively in mSUGRA [30,31]. In Fig. 3, we present the relic density of the neutralino dark matter versus $m_{1/2}$ for $\tan\beta = 3$ and $\tan\beta = 35$. When $\tan\beta \sim 35$, the ISM model and mSUGRA generate comparable neutralino relic densities. For $\tan\beta \sim 3$, the heavy sfermions reduce the annihilation cross section of $\chi_1^0\chi_1^0 \to f\bar{f}$ and correspondingly increase the neutralino relic density. Therefore, the value of $\Omega_{\chi_1^0} h^2$ is larger in the ISM model with the same parameters.

V. CONCLUSIONS

The three processes considered in this Letter will be complementary in distinguishing the inverted-scalar-mass hierarchy model and the minimal supergravity model. If the nature favors small $\tan\beta \sim 3$, searches for the trileptons from $\chi_1^\pm\chi_2^0$ production at the upgraded Tevatron can be made up to a larger chargino mass in the ISM model for $m_0 \gtrsim 200$ GeV. The mSUGRA predictions for trileptons show a strong dependence on m_0 at low $\tan\beta$, but the ISM predictions do not. The mSUGRA model has a larger parameter space for a cosmologically interesting relic density of the neutralino dark matter. At high $\tan\beta \gtrsim 35$, the experimental constraint from $B(b \to s\gamma)$ allows more parameter space in the ISM; the branching fraction in mSUGRA is typically too small unless the charginos and the charged Higgs boson are very heavy.

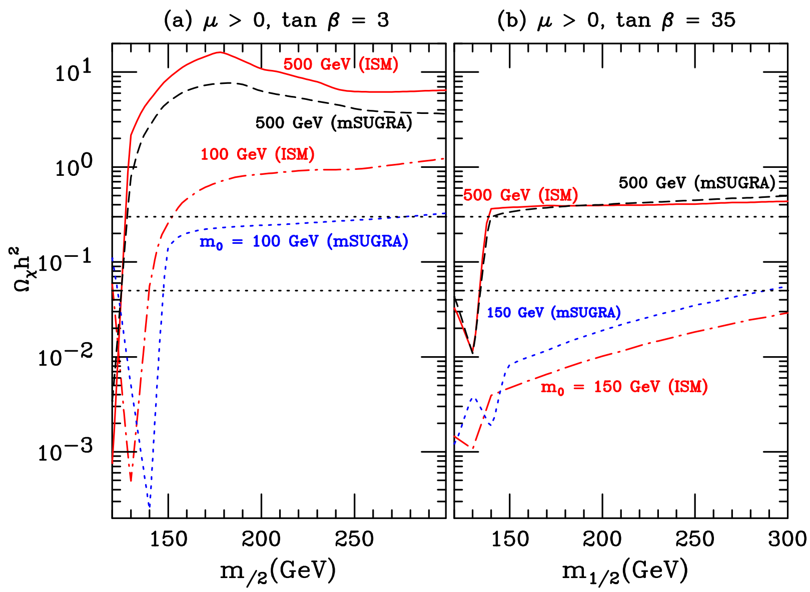

FIG. 4. $\Omega_{\chi_1^0}h^2$ versus $m_{1/2}$ for $\mu > 0$, (a) $\tan\beta = 3$ and (b) $\tan\beta = 35$ with $m_0 = 100$ GeV or 150 GeV in the ISM (dot-dash) and the mSUGRA (dot) models as well as $m_0 = 500$ GeV in the ISM (solid) and the mSUGRA (dash) models. The horizontal dotted lines denote $\Omega_{\chi_1^0}h^2 = 0.05$ and 0.3.

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